PARTIAL DISCHARGE MODELLING AND MEASUREMENT OF HV INSULATION

A Thesis Submitted in Partial Fulfilment
of the Requirements for the Award of the Degree of

Master of technology
in
Power electronics and drives

By

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CERTIFICATE

This is to certify that the thesis entitled, "**Partial discharge modeling and measurement of HV insulation**" submitted by **Ashirbad Purohit** for partial fulfillment of the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in Power Control and Drives during 2014 - 2015 at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:

Place:

Prof. S. Karmakar
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CONTENT

Abstract

Insulation of high voltage power equipment is very much important for their safe and reliable operation. The insulating material is of solid, liquid or gaseous forms. Most of the insulating material cannot be designed without having impurities inside it. Presence of defect or impurities in the insulation creates weak spot in the insulation and leads to local field enhancement surrounding the insulation and very cause of partial discharge. It is observed that PD is one of most pronounced cause of failure of insulation in HV power transformer and HV cable. So, insulation condition assessment is very much necessary for safe and reliable operation of power system network. In this work a MATLAB based SIMULINK model is developed for cable insulation considering all its design parameter and to generate PD pulses a void is considered in insulation of cable. In addition to that PD in transformer oil insulation is detected using electrical method and ultra-high frequency detection method by using antenna.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

PD	Partial discharge
HV	High voltage
KV	Kilo volt
PDIV	Partial discharge inception voltage
XLPE	Cross link polyethylene
UHF	Ultra high frequency
RF	Radio frequency
EM	Electro magnetic

LIST OF SYMBOL

Symbol	Name of symbol
C_C	Capacitance of void
C_b	Capacitance of rest of the part of insulation in series to void
C_a	Capacitance of rest of the part of insulation in parallel to void
V_{in}	Input voltage
R_{in}	Input resistance
R_c	Cable resistance
L_c	Cable inductance
G_{cs}	Conductor screen conductance
C_{cs}	Conductor screen capacitance
G_{is}	Insulation screen conductance
C_{is}	Insulation screen capacitance
G_{sb}	Screen bed conductance
C_{sb}	Screen bed capacitance

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Insulation quality plays utmost importance in HV power cable and HV transformer. PD is main cause of degradation of insulation quality. PD occurs as there is impurities or void in the insulation. Design of cable insulation involves man, material and machine .so, it is impossible design cable insulation without having impurity. In case of transformer oil insulation defect may arise due to protrusion from transformer winding and floating conducting or non-conducting particle residing in transformer oil. The non-conducting defect originate from paper insulation surface or press board .Conducting defect due to wear and tear of metal parts of oil cooling system during operation. HV cable and power transformers are very much expensive so extending their life not only economical but also very essential for safe and reliable operation of power system network. So, it is very much essential detect PD as it is one of most prominent cause of failure of HV cable and power transformer.

1.2 LITERATUREREVIEW

PD has been regarded as one of major source of insulation condition degradation. So, many researchers have tried to detect and measure PD in order maintain safety and reliability of power system networks. W. L. Weeks and Yi Min Diao have evaluated effect of semiconducting screen, conductors and surrounding earth on propagation characteristics of transient wave in power cable[5]. Gavita Mugala and Roland Eriksson have developed an approximate model which can analyze how different part of conductor and dielectric can contribute to the losses occurred[4]. Yukata Miyamoto, and Naoto Nagaoka have derived semiconductor layer impedance formula based on Maxwell equation to evaluate effect of semiconductor layer during wave propagation on cable [19].During initial days loop antenna used as transmitter and receiver for RF application [16]. Advantage of using loop antenna is its manufacturing cost is very low. Sriyono,Yongjoo kim,Umar khayam,Suwarno, masuki hakita have investigated PD in power apparatus using loop antenna[17]. P. J. Moore, I. E. Portugues, and I. A. Glover have investigated PD using wide band RF antenna [18].

1.2 RESEARCH MOTIVATION

The PD phenomena in insulation of high voltage power equipment is main cause of its failure. Though cable insulation designed with great care, impurities in it cannot be avoided.so it causes degradation of HV power cable. The presence of minor defect in transformer oil leads to local field enhancement causing partial discharge. The defect is due to projection from the winding or due to floating conducting/non-conducting particles present in the transformer oil.so it is very much necessary to detect PD in high voltage insulation for safe and reliable operation of power system network.

1.3 OBJECTIVES OF THE PROJECT

- Modeling of high voltage cable considering all its design parameter
- To detect PD inside cable considering a cylindrical void inside cable insulation using MATLAB in SIMULINK environment.
- TO observe PD activity inside transformer oil in high voltage laboratory using electrical detection method and UHF detection method.
- To compare PD activity observed in above two mention technique.

1.5 THESIS OUTLINE

Chapter 1 This chapter focuses on basics of proposed work. It highlights motivation and objective of the project.

Chapter 2 It covers basic concept of partial discharge and necessity of detection of PD in HV cable and transformer oil insulation. It enlightens us about types of PD and different methods of detecting it.

Chapter 3 discussed about modeling of PD in HV cable insulation considering all design parameter.

Chapter 4 includes details of experimental work performed to detect PD inside transformer oil insulation and the outcome of experiment

Chapter 5 This chapter highlights conclusion drawn from the work done and also indicates possible research that can be done in future

CHAPTER 2

BASIC CONCEPT OF PARTIAL DISCHARGE

2.1 Introduction

2.2 Necessity of PD detection

2.3 Classification of PD

2.4 PD under alternating voltage condition

2.5 Types of PD detection method

2.1 INTRODUCTION

Partial discharge is a localized discharge which may or may not bridge the gap between electrodes partially. Process of manufacturing insulation comprises many stages which include selection, preparation and processing of raw material and also thermal or chemical treatment if necessary. Providing electrical insulation for HV apparatus comprises man, machine, raw material and also effect of environment. So it is difficult to have a perfect electrical insulation without having voids or impurities. Some type of defects are air bubbles, voids, micro-cracks, improper contact between insulation and conducting surface, de-laminating of varnish in winding wire etc. As probability of occuring defects in transformer oil and cable insulation is very high, partial discharge is pronounced which leads to severe damage of it there by affecting reliability and safety of high voltage power system network.

2.2 NECESSATY OF PD DETECTION

The process of manufacturing of cable insulation comprises selection, preparation, processing of material and again it is subjected to different environmental condition .As the process involve man, machine ,material and different environmental condition a perfect electrical insulation hard to achieve without having any impurities .In case of transformer oil defect may arise due to protrusion from transformer winding and floating conducting or non-conducting particle residing in transformer oil. The non-conducting defect originate from paper insulation surface or press board .Conducting defect due to wear and tear of metal parts of oil cooling system during operation. These imperfections are cause of partial discharge. Though PD magnitudes small in quantity, it degrades the insulation condition severely.so PD detection is must to maintain reliability and integrity of power networks.

2.3 CLASSIFICATION OF PARTIAL DISCHARGE

2.3.1External partial discharge

External PD are those which occurs outside the power apparatus.

2.3.2 Internal partial discharge

It occurs inside the high voltage power equipment. Presence of defects in insulation creates weak spot in insulation i.e. dielectric strength of defected part is less than that of insulation. When electric field strength outside the defected part exceeds electric field strength inside defected part leads to partial discharge.

(a) Corona discharge

(b) Surface discharge
(c) Treeing channel.

(d) Cavity discharge:

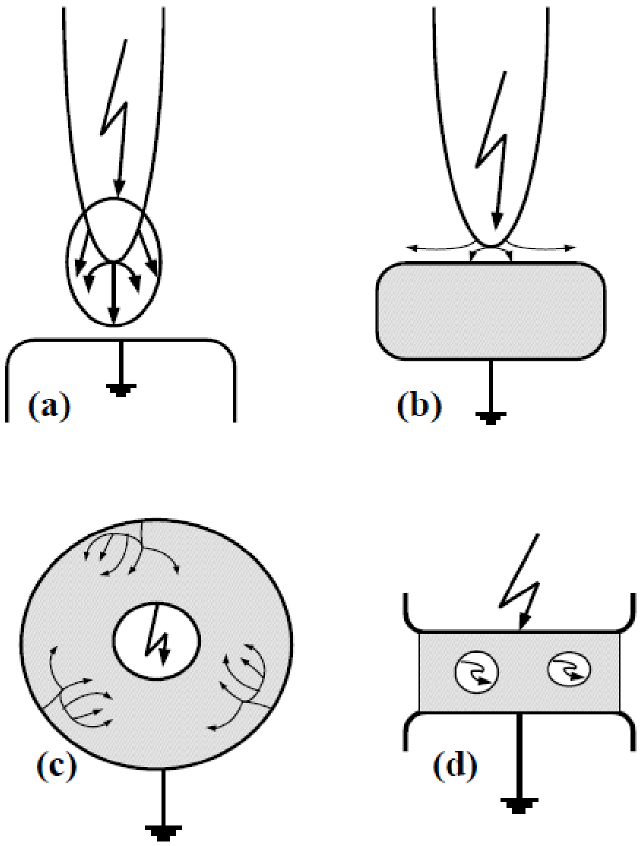

FIGURE 2.1: Various type of PD in insulating material (a) corona or gas discharge (b) surface discharge (c) treeing channel (d) cavity discharge

2.4 PD UNDER ALTERNATING VOLTAGE CONDITION

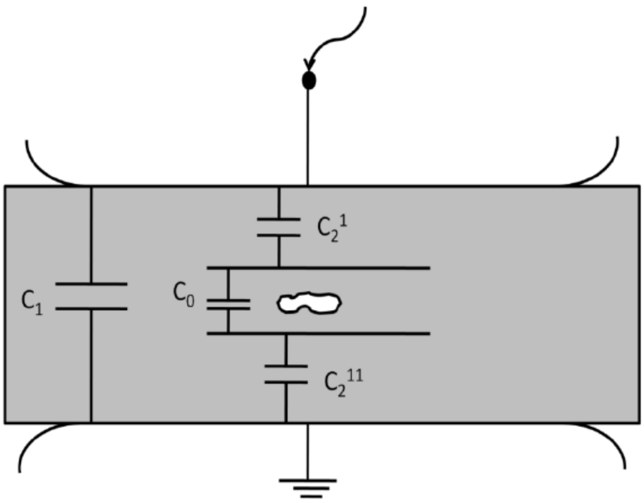

Figure 2.2(a): Gaseous defect in solid dielectric condition

Where,

C_0 is the capacitance of defected part . C_2' and C_2'' are capacitance of healthy part of insulation in series with void.C_1 is capacitance of rest of healthy part of insulation in parallel to gaseous void.

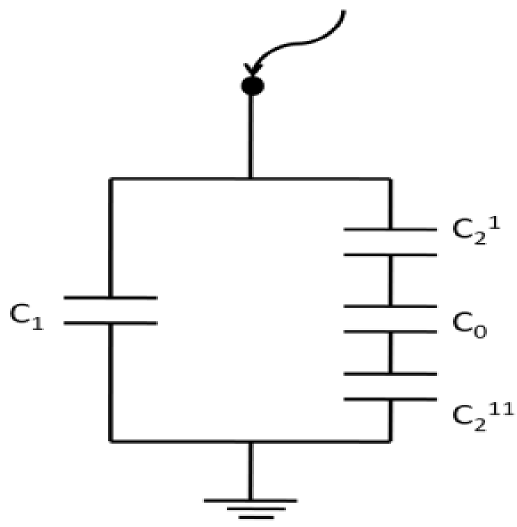

Figure 2.2(b) Equivalent circuit of figure 2.2 (a)

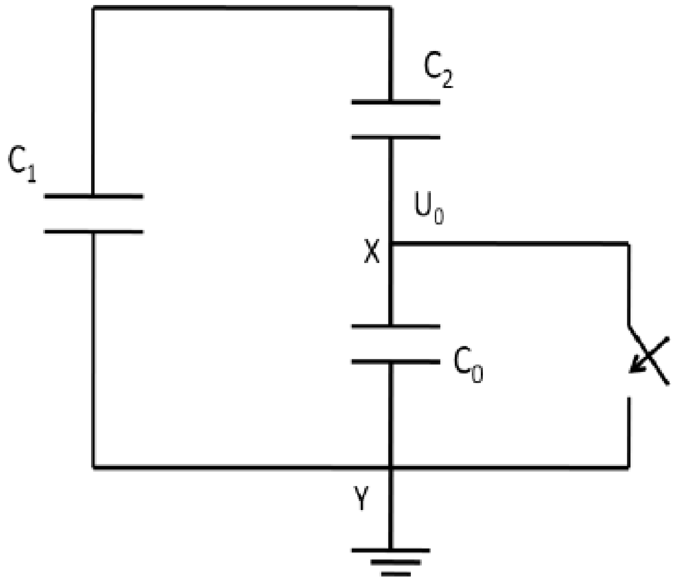

Figure 2.2(c) equivalent circuit of PD where closing of switch indicate PD phenomena started

2.5 TYPES OF PD DETECTION METHOD

There are many popular method for PD detection. These are

- optical detection method
- Electrical detection method
- Acoustic detection method
- UHF detection method

2.5.1 Optical detection method

In this method of detection appearance of discharge is due to dissipation of light which takes the form of ionization during excitation process. Light emitted in this method depends upon temperature, pressure and nature of insulating material. For this detection method insulating material used are of transparent type. This method possesses drawbacks in high voltage transformers as mineral oil which it contains is of opaque nature.

2.5.2Electrical detection method

Electrical method of detection is frequently used and widely popular method for measurement of partial discharge in power equipments . Electrical method of detection method is useful for modeling of PDs inside the cable insulation. It emphasizes upon presence of the current as well as voltage pulses which are caused by current streamer due to presence of void and impurities. Duration of pulses are less than one second and range of frequency variation in KHz, Shape of pulses and its appearance at different phase locations gives information about PD types and information regarding insulation failure. Time domain recording device is employed for recording of partial discharge impulses in this detection method.Various signal processing techniques are useful for PD signal identifications. Electrical method of detection is useful for online electrical PD detection. During operation of HV power equipment broadband and narrow band electrical pulses are encountered . It is very difficult to classify those electrical noisy signals and PDs. The pulses that appeared in this method of detection depends on the physical dimension of high voltage cables. This method of detection has several disadvantages but finds wide usefulness in power plants It helps the power engineers and technicians by giving necessary as well as vital contents regarding the characteristic, appearance of different type of partial discharge as well as regarding the insulation failure occurance in high voltage power equipment like transformer, generator, cable etc.

2.5.3Acoustic detection method

Acoustic detection method based on sound waves produced during PD phenomena. This sound, audible or not, is due to current streamer formed in the event of PD and the material surrounding the streamer is vaporized. This kind of vaporization leads to release of mechanical energy , which propagates by taking the form of a pressure field. The best possible example is the occurring of thunder after a lightning strike.

Acoustic detection systems divided into two types: external and internal systems. External acoustic detection systems frequently used these days, uses sensors which are kept outside to power apparatus to detect acoustic signals which are originated in the course of PDs. In internal systems sensors are placed inside of power equipment so that sound pressure wave can be measured directly.

Acoustic method of detection encounters so many limitations. As the acoustic PD signal propagation are of complex nature, acoustic method of detection finds difficulty to detect it. Sometime acoustic signal detected posses very low intensity so we need a highly sensitive sensor which can detect minute changes in signal. . One other very important issue which currently limits the usefulness of acoustic PD detection equipment is the high price for these units. Therefore the question arises if such detection systems cannot be made cheaper by using mass produced components like commercially available piezoelectric transducers and other off-the-shelf components.

2.5.4UHF detection method

Unconventional PD measurement (UHF) has great advantage like immunity against disturbances as compared to other conventional technique .Condition monitoring of high voltage equipment both on site and online can be performed by UHF PD detection method. UHF detection by means of antenna has no connection to power transformer like other methods .it is immune to electromagnetic interferences so able provide high signal to noise ratio.

CHAPTER-3

MODELING OF PD INSIDE CABLE INSULATION CONSIDERING ALL DESIGN PARAMETER

3.1 Parameters of cable investigated

3.2 Electrical equivalent model of PD in cable insulation including all its design parameter

3.3 Simulation result and discussion

3.1 PARAMETER OF CABLE INVESTIGATED

A 33 kV cable is considered for modeling of partial discharge. The cable has single core, XLPE insulation and metallic screen placed inside the screen bed.

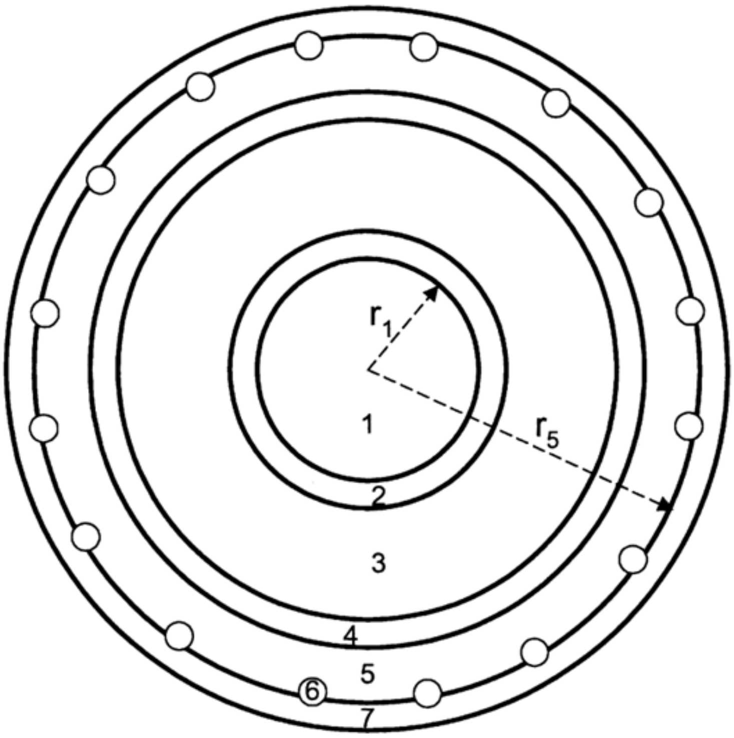

Figure 3.1 Cross sectional view of cable investigated

Where,

r_1-radius of the conductor

2- screen of conductor

3- insulation

4- screen of insulation

5-screen bed

6-metallic screen made up copper conductor

7-outer insulation $r_5$radius of metallic screen

Table-1: parameters of cable shown in figure 3.1

Parameter	Dimension(in mm)
$\mathbf{r_1}$	8.7
Thickness of XLPE insulation	1.0
Thickness of insulation screen	8.8
Thickness of conductor screen	0.4
$\mathbf{r_5}$	15.8
Thickness of PE jacket	2
Radius of one screen wire	0.4
Number of screen wire	44

3.2 ELECTRICAL EQUIVALENT MODEL OF PD IN CABLE INSULATION CONSIDERING ALL DESIGN PARAMETER

3.2.1 SERIES IMPEDANCE

With reference to figure 3.1 series impedance of cable is due to cable conductor and the metallic screen. Internal impedance of conductor $\boldsymbol{Z_{1c}}$ and metallic screen $\boldsymbol{Z_{6c}}$ constitutes internal impedance and geometrical impedance of cable makes up external impedance $\boldsymbol{Z_{ec}}$.So total series impedance $\boldsymbol{Z_c}$ is

$$Z_c = Z_{1c} + Z_{ec} + Z_{6c}$$

The total series impedance given by formula

$$Z_c = \frac{1}{2\pi r1}\sqrt{\mathrm{j}w\mu_0/\delta_1} + \frac{\mathrm{j}w\mu_0}{2\pi} ln\frac{r_5}{r_1} + \frac{1}{2\pi\rho n}\sqrt{(jw\mu_0)/(\delta_6)} \quad (3.1)$$

Where,

r_1 = radius of conductor

r_6 = radius to metallic screen

δ_1 = conductivity of conductor

δ_6 = conductivity of free space

Table-2: Calculated values of cable series impedance using equation (1)

Resistance(R_c)	5.25×10^-5 ohm
Inductance(L_c)	5.3×10^-4 henry

Semiconductor screen, XLPE insulation and screen bed contribute to the shunt admittance. Admittance is given by formula:

$$Y=\frac{1}{\sum_{K=1}^{n} 1/y_k} \qquad (3.2)$$

Each layer admittance is due to its geometrical capacitance c_0 and complex capacitance c^*.

So, $Y = jwc^* = jw\frac{\epsilon_0 \epsilon_r^*}{d}A$

Complex permittivity is given by equation:

$$\epsilon_r^* = \frac{A_1}{1+(jw\tau_1)^{1-\alpha_1}} + \frac{A_2}{1+(jw\tau_2)^{1-\alpha_2}} + \frac{\partial_{dc}}{jw\epsilon_0} + \epsilon_\infty \qquad (3.3)$$

Where,

τ_1 and τ_2 relaxation time

∂_{dc} is dc conductivity

A_1 and A_2 amplitude factors

ϵ_∞ high frequency component of complex permittivity

α_1 and α_2 broadness of relaxation peak

It is described by

- two cole-cole function
- one dc conductivity term
- high frequency permittivity term

XLPE insulation of cable is modelled with complex permittivity 2.3-j0.001

Table-3: parameter of dielectric function described by equation (3.3)

Parameter	Conductor screen	Insulation screen	Screen bed
α_1	0.5	0.3	0.5
τ_1(in sec)	300	100	800
A_1	105	95	160
α_2	0.3	0.5	0,7
τ_2 (in sec)	o.68	4	15
A_2	50	90	48
ϵ_∞	4	2	1
$\partial_{dc}(^{ms}/_{m})$	0.15	2.7	32

Table-4: calculated values of all the design parameter from equation (3.3)

Parameter	Conductance(in mho)	Capacitance(in farad)
Conductor screen	0.012	2.86×10^-9
Insulation screen	0.58	3.8×10^-9
Screen bed	7.855	4.6×10^-7

Table-5: calculated value for XLPE insulation

Parameter	Conductance(in mho)	3.36×10^-11
XLPE insulation	Capacitance(in farad)	2.46×10^-10

3.2.3 Modeling of void in cable insulation

Let a void of height 0.1 mm and radius 0.2 mm considered in XLPE insulation. Due to presence of void insulation takes form of 3 capacitance model shown in figure .The capacitance of region where discharge takes place is C_c .C_b Represents capacitance of healthy part of insulation in series to void.C_a represents capacitance of rest of healthy part of insulation in parallel to void.

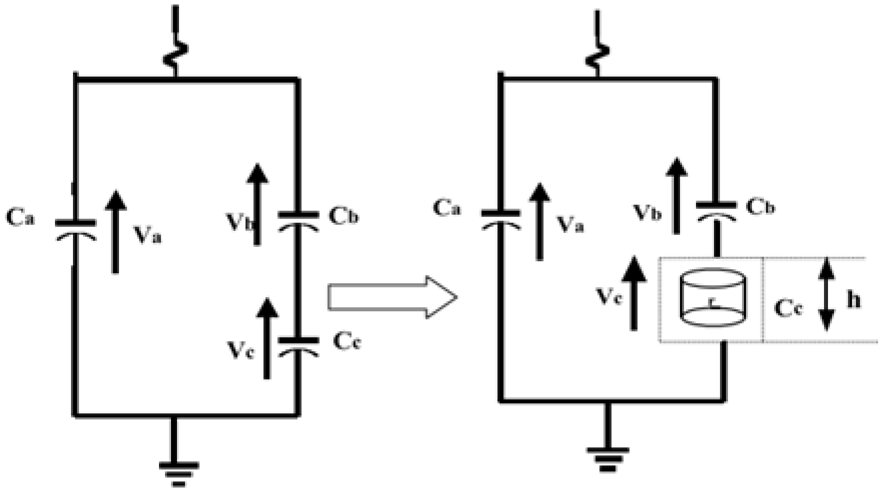

Figure 3.2 three capacitance model of insulation due to presence of void

Where,

$$C_a = \frac{\epsilon_0 \epsilon^*}{t} (l - 2r) b$$

$$C_b = \frac{\epsilon_0 \epsilon^*}{t-h} (\pi \times r^2)$$

$$C_C = \frac{\epsilon_0}{h} (\pi \times r^2)$$

3.2.3 Electrical equivalent model of PD in cable insulation considering All design parameter

The Simulation model consist of a complex network having cable impedance in series path and shunt admittance in parallel path. A variable voltage source is applied to the circuit to observe PD phenomena. A high value series impedance connected to voltage source to limit current in the circuit. Measuring capacitor and coupling capacitor connected in parallel to measure applied voltage and low level of PD respectively.

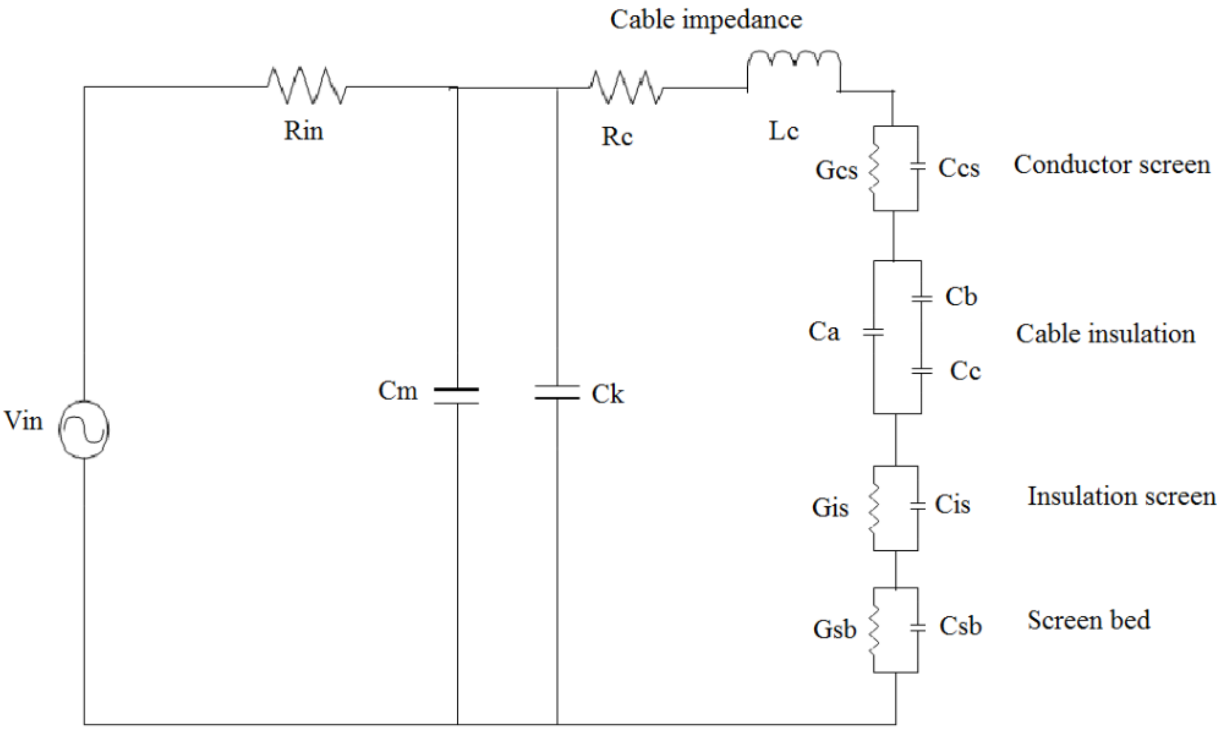

Figure 3.4 Electrical equivalent model of cable considering void in insulation

3.3 SIMULATION RESULT AND DISCUSSION

To simulate PD activity inside cable insulation MATLAB based Simulink model proposed in this work. Voltage applied across Simulink model increased gradually to observe voltage at which significant amount of PD signal occurring. In figure 3.1 PD signal obtained at 9 kV of applied voltage.

From above simulation result it is concluded that PDIV for investigated cable is 9KV.further as applied voltage is increased the PD magnitudes increases. In above simulation result significant amount of PD occurs at 20 degree of applied voltage in negative direction. Next significant PD visible at 140 degree and 250 degree which is in positive direction

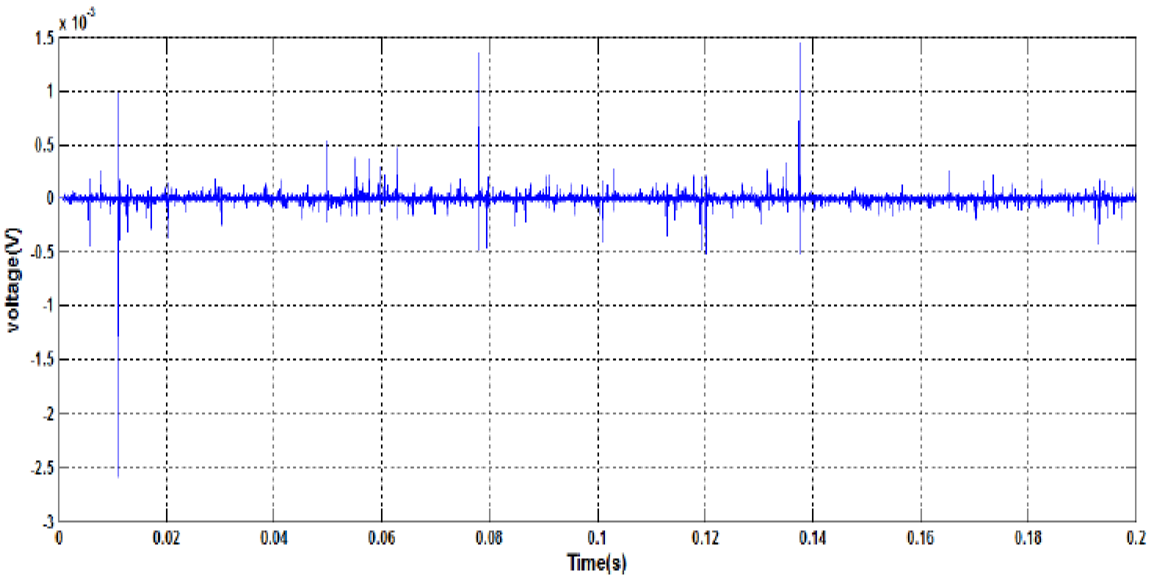

Figure 3.3.1: PD signal obtained at 9 KV of applied voltage

CHAPTER 4

PD MEASUREMENT IN TRANSFORMER OIL BY ELECTRICAL METHOD AND ANTENNA

4.1 Introduction

4.2 UHF sensor for PD detection

4.3 Experimental setup

4.4 Result and discussion

4.1 INTRODUCTION

High voltage transformers are very important part of power system network. Any damage to HV transformer effects safety and reliability of power system network. To prevent outage of transformer accurate assessment of transformer insulation is very much necessary. PD is a well-known phenomenon that degrades oil insulation of transformer, so it is necessary to detect PD. Several PD detection method has been prescribed till date. Among them electrical detection method is very popular and UHF detection method gaining popularity now a days. The UHF detection method by means of antenna is a non contact method i.e. it detects electromagnetic radiation originated due to partial discharge, whereas electrical method is a contact method i.e. it detects PD current pulses of high rise time and high fall time across a coupling capacitor. Now a days UHF detection method is gaining popularity due to

- immune from external disturbance signal
- no electrical connection of sensors required to HV circuit
- capability of determining failure location

4.2 UHF SENSOR FOR PD MEASUREMENT

Here a loop antenna is designed to detect electromagnetic pulses radiated due to occurrence of PD. Main function of antennas are to transmit and receive signal. To achieve characteristics of an antenna a copper conducting coil of 30 cm length wound around a female connector forming small loops of diameter 1cm.

A loop sensor is designed such that voltage induced in it is maximum at a particular frequency where it resonates. Design of loop antenna based on faraday law of electromagnetic induction i.e. time varying magnetic field passes through closed surface formed by loop antenna induces voltage which is described by

$$V_{ind} = -N\frac{d\Psi}{dt}$$

$$\Psi = \int B \, dS$$

Where,

N= total turns

Ψ=flux linkage

B=magnetic flux density

S= surface area of loop

Figure 4.1 Antenna used in laboratory to detect EM radiations

A loop antenna to detect PD in oil insulation designed based on equation

$$C=\lambda .f$$

As loop antenna is manufactured to detect EM wave induced by PD up to frequency 100MHZ. Length of loop antenna kept 30 c.m. as length of loop antenna must be one tenth of wavelength of antenna.

4.3 EXPERIMENTAL SETUP

An experiment performed in a modeled transformer tank of 25 c.m. ×20 c.m.×15 c.m. To model PD inside oil point plane electrode system used. Void or defect in oil is created artificially. A flat type electrode which is connected to ground holds the transformer oil paper insulation inside oil. A needle type electrode which is connected to secondary of transformer is pressed against the oil paper insulation so that void is created artificially. Since antenna is bidirectional in nature it is placed in 20 c.m. perimeter of test object.

The measurement setup is aimed to compare PD detected in transformer insulation. Modeled transformer tank connected to HV autotransformer and voltage is increased till significant amount of PD activity observed at 14.9 kV.

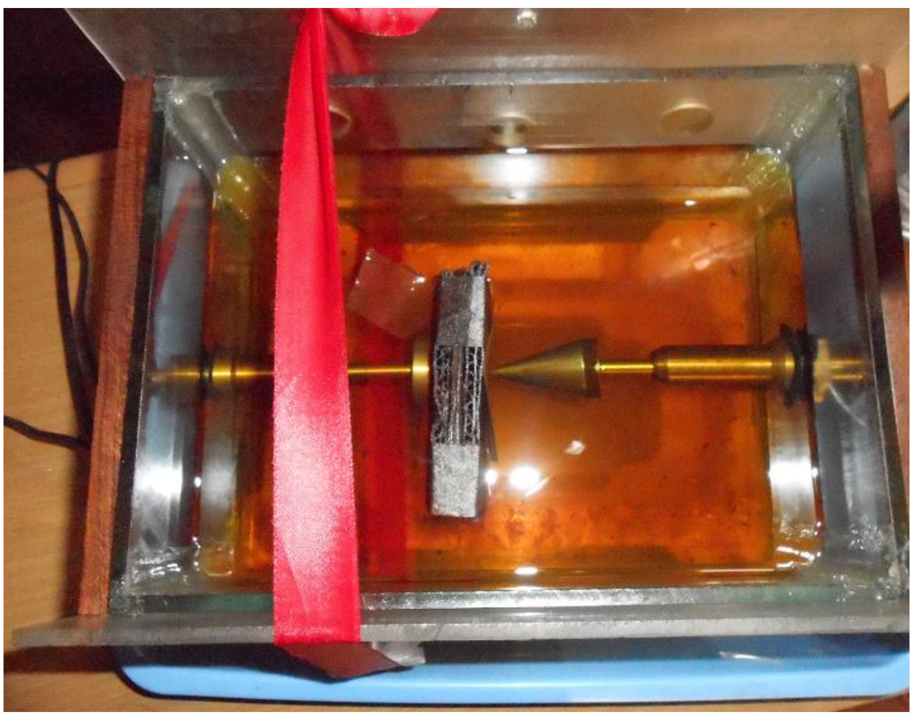

Figure 4.2: Modeled transformer tank to detect PD in HV laboratory.

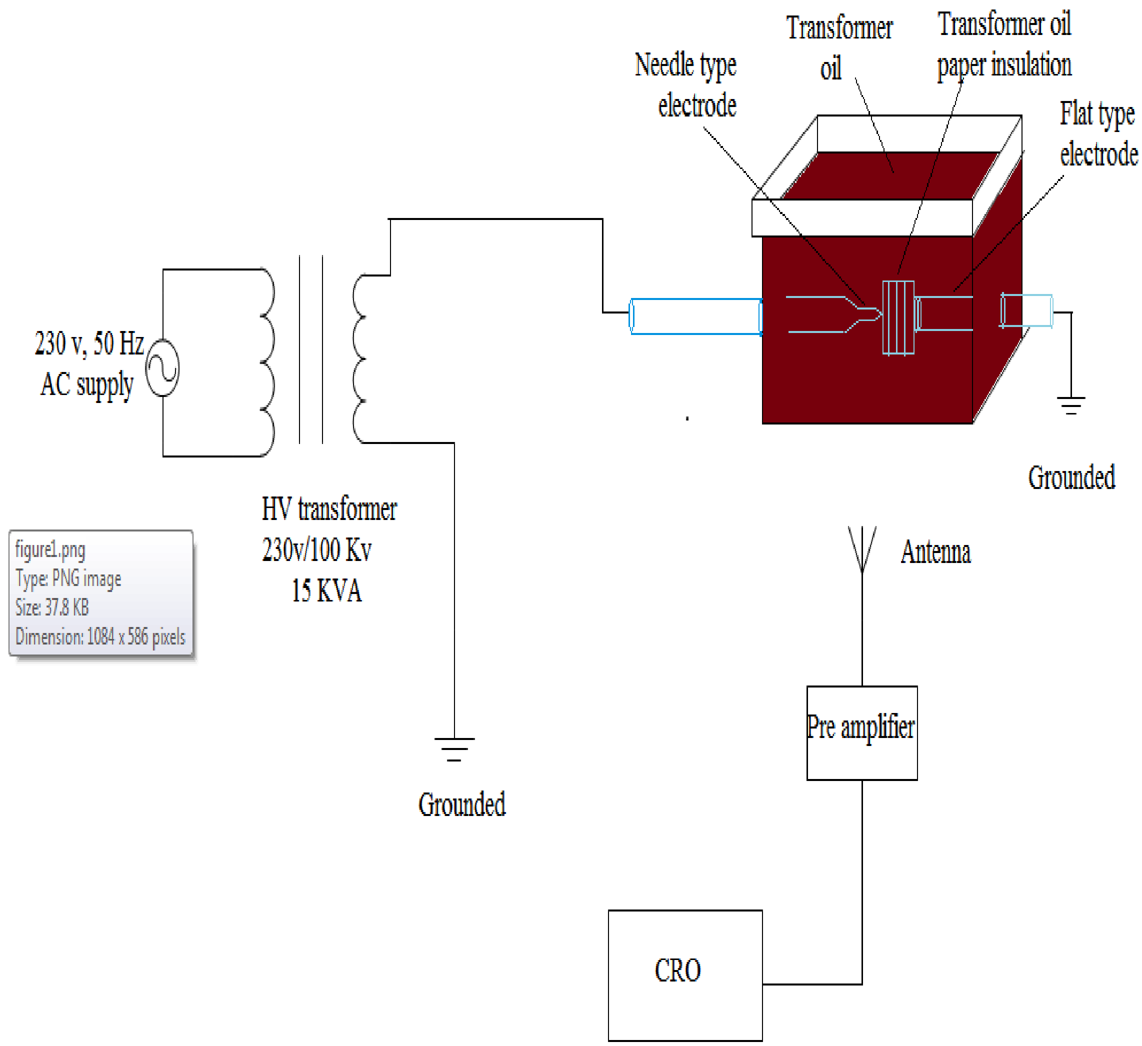

Figure 4.3: Schematic diagram of experimental setup to measure PD in transformer oil.

4.5 RESULT AND DISCUSSION

PD waveforms are taken across CRO screen for both electrical method and UHF detection method. A 100 kV, 1000 nf coupling capacitor connected in parallel to detect electrical PD pulse .Figure 4.4 signifies PD pulse in transformer oil where upper signal is detected by coupling capacitor and lower signal detected by antenna.

From figure 4.4 it is clear that PD activity is significant at 14.9 kV of applied voltage which is detected by coupling capacitor. But PD activity is not detected by antenna as it is placed outside the transformer tank. Antenna detects the electromagnetic radiations due to PD .As EM radiation attenuated by the transformer tank PD activity by antenna not significant.

Figure 4.4: PD pulses observed at 14.9 kV of applied voltage in transformer

Oil. Upper signal is measured by coupling capacitor and lower signal is measure by antenna.

Figure 4.5 corresponds to PD activity observed at 16.8 kV of applied voltage in transformer oil insulation. At 16.8 kV significant PD activity measured by antenna but number of PD pulses detected is less compared to PD pulses detected by coupling capacitor

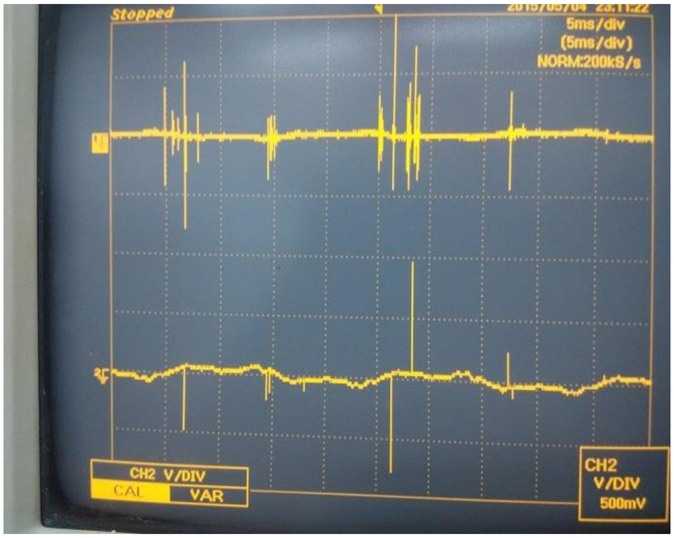

Figure 4.5 PD pulses at 16.8 KV of applied voltage in transformer oil insulation. Upper signal is measured by coupling capacitor and lower signal is measure by antenna.

Figure 4.6 correspond to PD activity measure at 22 kV of applied voltage. At 22 kV PD counts in antenna goes up i.e. antenna able to measure PD in oil more efficiently.

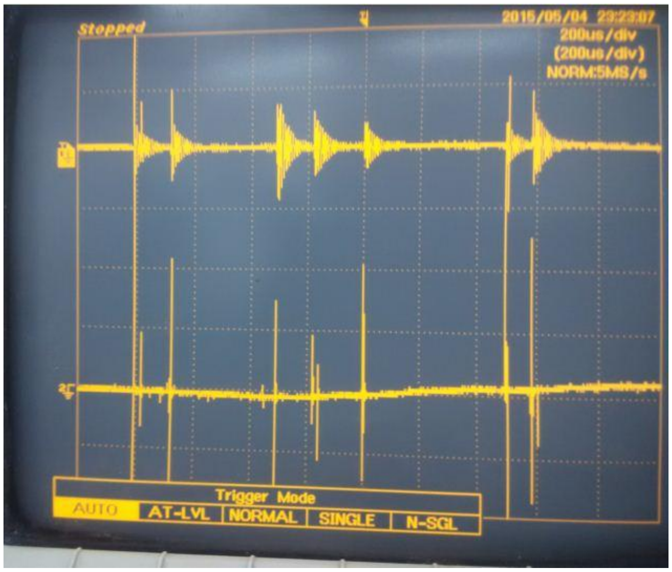

Figure 4.6 PD pulses at 22kv of applied voltage in transformer oil. Upper signal is measured by coupling capacitor and lower signal is measure by antenna.

Figure 4.4,4.5,4.6 are taken taking time per division setting at 10ms/div. Now to view actual pulse of PDs time per division of CRO taken at 1µs/div.From figure 4.7 it is observed that first significant PD pulse is detected by coupling capacitor but antenna detecting more number of significant PD pulses.So antenna is more proficient in detecting PDs.

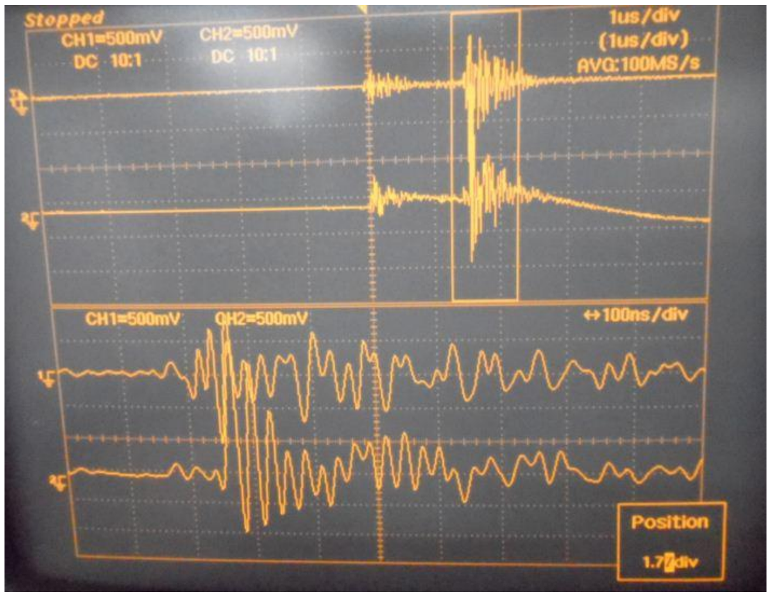

Figure 4.7.PD pulses observed at 19.5 KV in transformer oil. Upper signal is measured by coupling capacitor and lower signal is measure by antenna.

CHAPTER 5

CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 Conclusion

5.2 Scope for future work

5.1 CONCLUSION

In this work modeling of HV cable done considering all the design parameters and to get PD pulses a void is considered in the insulation. The model is implemented in MATLAB SIMULINK environment to get PD pmeasured by both contact method and non-contact method taken in single CRO screen and PDIV, number of PD pulses are compared.

5.2 SCOPE FOR FUTURE WORK

- Detection of PD activity in cable insulation by different detection method so that safe and reliable operation of HV cable can be achieved.
- Development of highly sensitive and multi resonant antenna to detect EM radiations emitted by PD signal.
- Detection of PD activity inside the transformer oil tank by placing antenna inside the oil tank

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